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A TERRAIN EVALUATION METHOD FOR PREDICTING TERRAIN SUSCEPTIBLE TO POST-LOGGING LANDSLIDE ACTIVITY

A Case Study from the Southern Coast Mountains of British Columbia

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ABSTRACT

A terrain evaluation method for predicting post-logging landslide activity is presented. The method is based on the analysis and integration of base data obtained from a landslide inventory and a terrain (surficial geology) mapping program, and is considered to be more objective and quantitative then previous approaches used in British Columbia. It involves four steps: (a) defining homogenous areas, referred to as terrain polygons, with respect to their surficial geology; (b) analysis of landslide site data to identify factors influencing clearcut landslides; (c) defining a set of terrain classes based on these factors such that each polygon can be assigned to only one class; and (d) grouping the classes into four stability ratings based on the ratio of the number of clearcut landslides to the number of clearcut hectares. The results of a case study are presented and include a computer generated landslide rating map and a comparison of landslide rates to documented changes in local precipitation records since 1940.

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INTRODUCTION

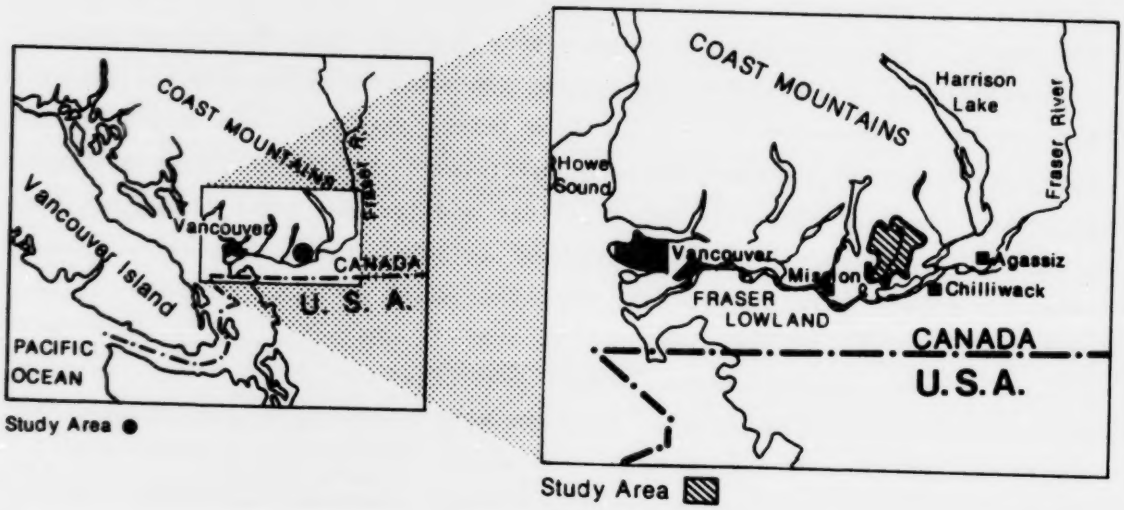
A number of methods for assessing landslide hazard by terrain evaluations have been undertaken for management and resource planning purposes. They range from simple inventories of existing mass movements to multiple-factor mapping of slope, geology, soils, and other terrain features (Sidle, et al, 1985). Examples of the latter include Bailey (1972), Bourgeois (1974), Hicks and Smith (1981), Ives and Bovis (1978), and Radbruch and Wentworth (1971), whereas Neilsen and Brabb (1977), and Wieczorek (1984) are examples of the landslide inventory approach. The terrain evaluation approach for predicting landslides following clearcut harvesting operations presented in this paper has evolved over a period of five years by contributions from several earth scientists. One of the basic concepts of the method, proposed at Slope Stability Mapping Workshop in British Columbia (Howes, 1982), requires that a detailed landslide inventory to be done in conjunction with a surficial geological mapping programme and that the landslide site data and the areal surficial geology data be integrated to identify terrain susceptible to landslides, particularly landslides generated following clearcut logging activities. This paper also outlined an initial framework for collecting, integrating, and presenting these different data sets. The method, in part, was applied to an area on the mid coast of British Columbia (Townshend, 1982). In this study, the surficial geology units identified during the mapping programme were grouped into unique terrain classes based on factors determined from a landslide survey. Although each class was assigned a qualitative slope stability rating following an earlier rating scheme (Bourgeois, 1974), it was the first application of defining terrain classes from observation of local landslides and subsequent rating of these classes. The method was developed further by Rollerson (1984), who applied it to a number clearcut blocks on the west coast of Vancouver Island in order to identify terrain susceptible to clearcut landslides; the results were presented by Sondheim and Rollerson (1985). This latter paper was important in that it introduced into the methodology a quantitative technique for assessing potentially unstable terrain by the calculation of landslide frequency rates on a unit area basis for different terrain classes, that in turn, were assigned a rating from a predefined slope stability rating scheme. Further details of this

statistical technique have been presented by Howes and Sondheim (1987) and Rollerson et.al. (1986). The terrain evaluation method presented in this paper is considered to be more objective and quantitative than terrain evaluation approaches for assessing landslide hazards previously used in British Columbia. In addition, the method provides an alternative to classical engineering studies for developing slope stability maps in forested watersheds where detailed precipitation, slope hydrology, and other physical data is limited, non-existent, or, if collected, highly variable (Rollerson, et.al. 1986). It is suitable for use by terrain or soil mappers who lack a strong background in classical slope stability modeling.

This study is the first large-scale project (150 km^2) in which the terrain evaluation method was applied to forested as well as clearcut landscapes. The purpose of this paper is to: (1) detail the terrain evaluation method for predicting landslide hazards; (2) present an example landslide inventory map and computer-generated landslide clearcut rating map; (3) describe some of the results of the landslide inventory study; (4) define the types of terrain with the greatest landslide potential following clearcut logging; and (5) compare natural and clearcut landslide rates on different types of terrain as well as comparing changes in these rates over time (since 1940) with documented long-term changes in local precipitation records.

PHYSICAL SETTING

The study area is located 65 km east of Vancouver, British Columbia, and includes the Norrish, Cascade, and Deroche drainage basins (Fig. 1). It is underlain by granitic rocks of the Coast Plutonic Rocks, except for the Deroche drainage basin, which is made up of Jurassic meta-volcanic rocks (Roddick, 1965). The valleys have been subject to multiple glaciations during the Pleistocene Epoch and were completely buried by ice during the most recent glaciation, the Fraser Glaciation (Armstrong, et.al. 1965). Most of the landforms and sediments in the study area are a result of this latter glaciation and subsequent postglacial events. Erosion by glacial ice rounded and smoothed the ridges and peaks, and oversteepened the valley side slopes. The ridge crests and upper slopes are overlain by a thin and, in places,



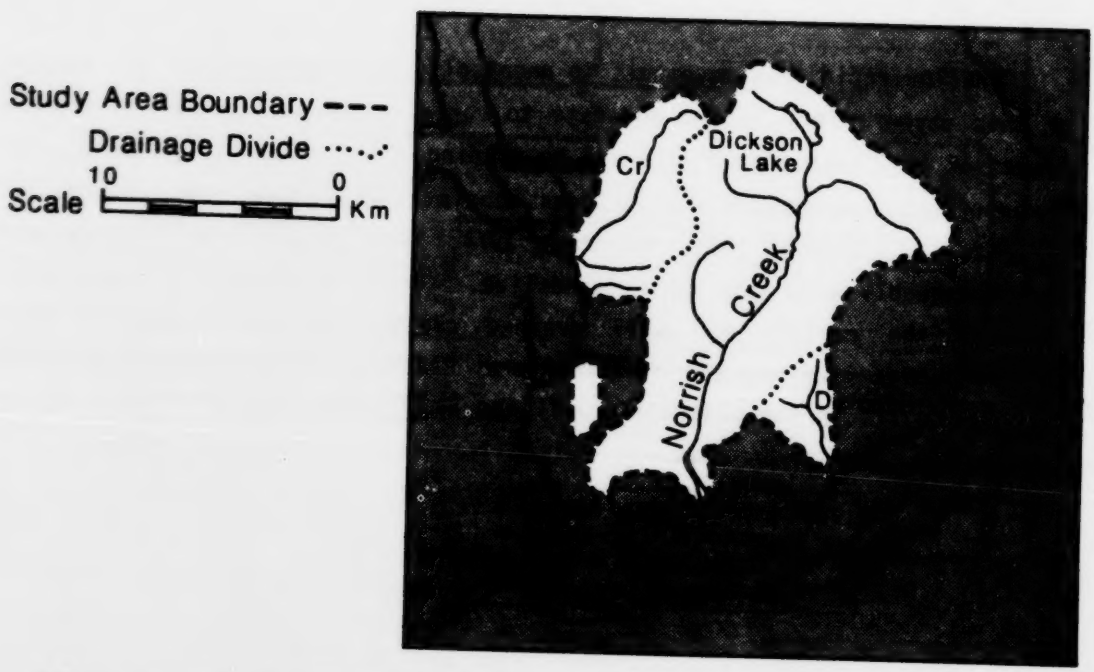
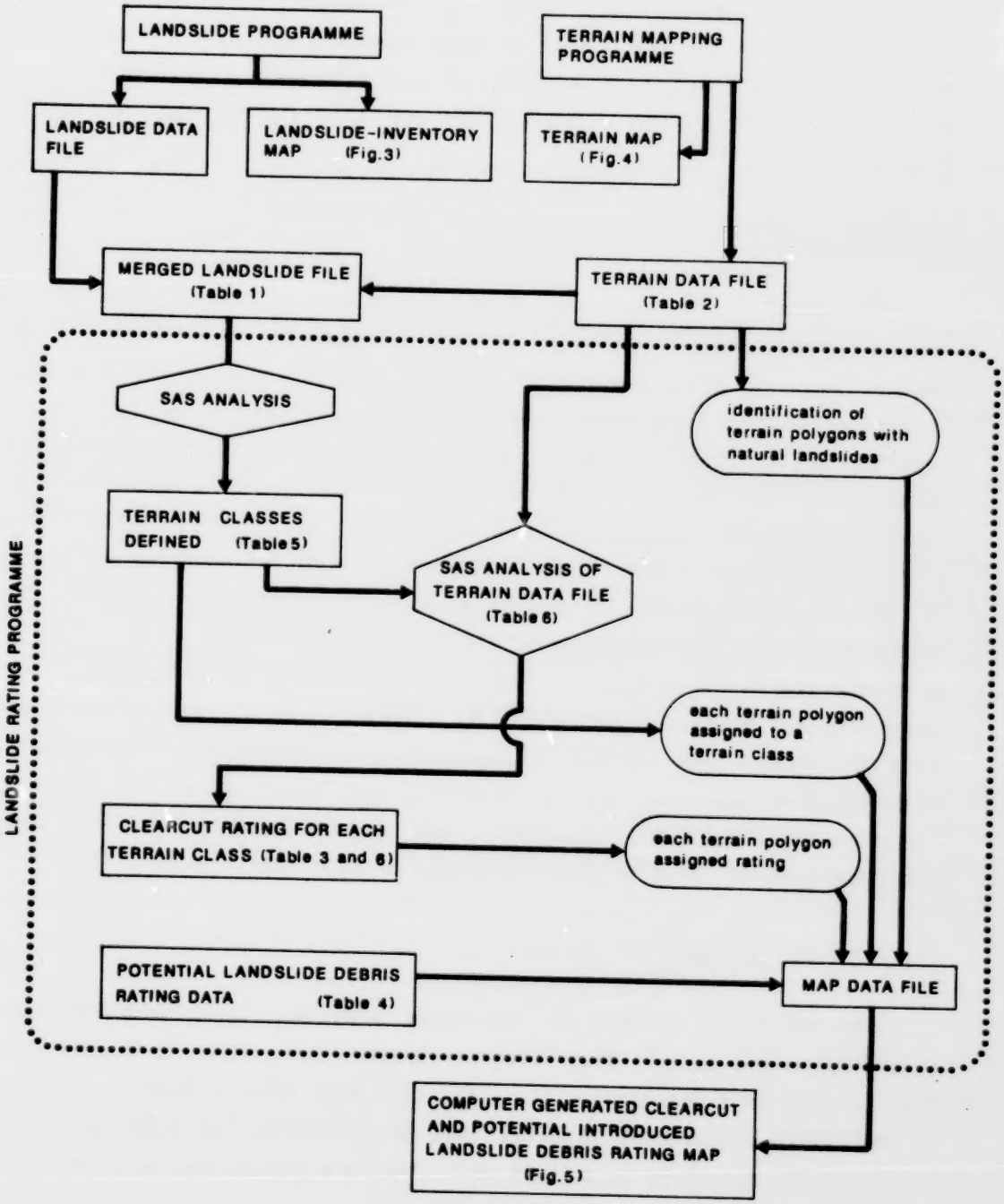


Figure 1: Location of study area

discontinuous mantle of glacial till or colluvium (formed by mass wastage processes in postglacial time) with rock outcrops. Lower valley side slopes are overlain by continuous and thicker till deposits with some local pockets of glaciofluvial gravels. Valley bottoms are occupied by deposits of glacial and glaciofluvial sediments, up to 30 m thick, that have been dissected by postglacial stream erosion to form multi-level terraces. Mass movement processes (such as rockfall, debris slides and torrents, and slumps) on the glacially oversteepened side slopes and alluvial fan accumulation, where steep tributary streams debouch into the main valleys, commenced after deglaciation and continue today. The area is characterized by cool, wet winters and dry, warm summers. Annual precipitation, based on records from Mission (221 m asl, Fig. 1), is 1772.1 mm with 69% of it falling between the months of October through March. The winter months are characterized by intense storms as reflected by 1-day and 3-day extreme precipitation totals of 92.6 and 123.0 mm, respectively, for a ten-year return interval (Coligado, 1982). These storms are considered to be one of the important triggering mechanisms of landslides.

DEFINITION OF TERMS

Shallow rapid mass movements in unconsolidated sediments for the purpose of this paper refers to the moderate to rapid downslope movement of shallow masses of non-consolidated material by sliding and/or flowing, commonly, over an impermeable substrate and includes debris slides, flows, avalanches, and torrents (cf. Sharpe, 1938; Swanston, 1974; and Varnes, 1958) and is used interchangeably with the term, landslide. Rapid drainage, as used here, includes the rapidly and well drained classes of the System of Soil Classification for Canada (Agriculture Canada, 1974) whereas moderate drainage refers to the moderately well and imperfectly drained classes of the same system.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TERRAIN MAPPING PROGRAMME
LANDSLIDE DATA FILE
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TERRAIN MAP (Fig.4)
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Figure 2: Flow chart illustrating the methodology for prediction of terrain susceptible to clearcut landslides

METHODOLOGY

The terrain evaluation method used to develop a clearcut landslide rating scheme for the study area is based upon the analysis and integration of base data obtained from a landslide and a terrain (surficial geology) mapping programme. The various steps of this method are outlined in Figure 2.

Landslide Programme

The objective of the landslide programme was to collect site specific data about individual landslides in order to gain an understanding of what factors and site characteristics influence natural and clearcut landslides. Landslides with a minimum area of 100 m^2 were identified on 1:15 000 and 1:20 000 scale, black and white, vertical photography flown in 1940, 1962, 1968, 1979, and 1981. Geomorphic features and criteria used for their identification is summarized in Howes (1981) and Sharpe (1938). Each landslide was given a unique identification code and its location was plotted on the air photographs. Site data about each landside were obtained from interpretation of air photographs, field observations (20% of the landslides were observed in the field), and the terrain data file of the terrain mapping programme (see below) and was stored in a merged landslide file. The type of data collected for each landslide is summarized in Table 1. A landslide-inventory map was produced by the plotting of the landslide locations on a 1:20 000 topographic map and attaching an expanded legend detailing some of the site characteristics of each landslide (Fig. 3).

Terrain Mapping Programme

The surficial geology of the study area was classified and mapped according to the Terrain Classification System (ELUC, 1976; Ryder and Howes, 1984). This is a descriptive classification that details several attributes of the various surficial deposits that occur within the study area. The object of the system is to delimit areas that are homogeneous with respect to

Table 1: Summary of data in merged landslide file

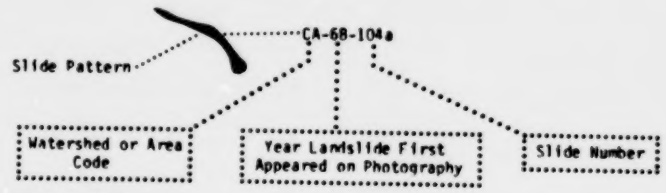
Summary Table of Data in the Merged Landslide File

Air Photographs[1]	Field Observations[1]	Terrain Data File[1]
location of failure	material at origin	material at origin
type of failure	type of failure	slope angle at origin
land use at origin	slide dimensions	drainage
slide dimensions	slope angle at origin	polygon number
vegetation status	vegetation status	
impact on stream system	drainage conditions	
aspect	aspect	
slope configuration	type of failure plane	
year appeared on photos	permeability	
	texture of material	

[1] SOURCES OF DATA

Explanation of Map Symbols

Each landslide is portrayed on the map by a pattern with a combination of letters and numbers attached to the pattern



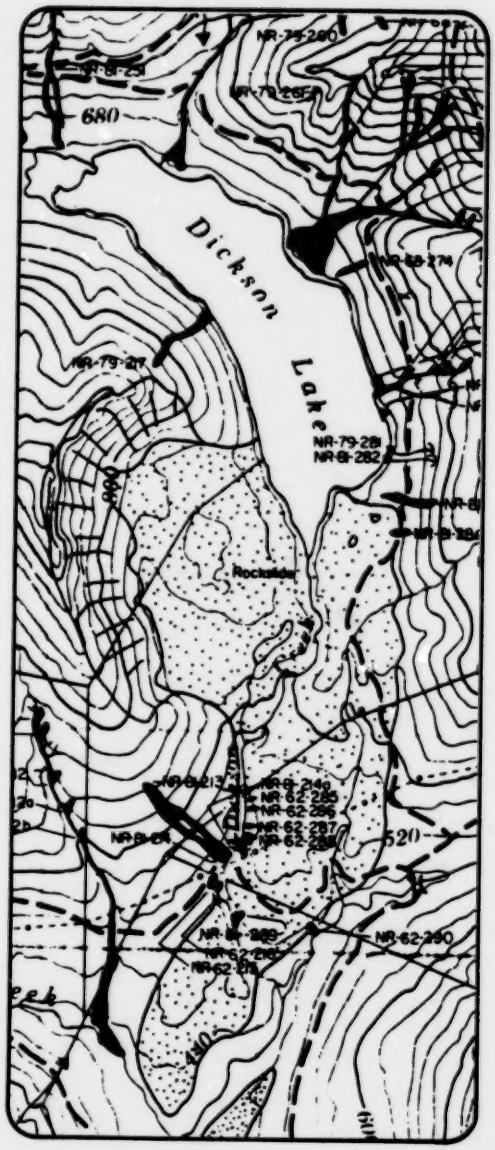
NR - Norrish Creek	40 = 1940
CC - Carrot Creek	62 = 1962
CA - Cascade Creek	68 = 1968
DE - Deroche Creek	79 = 1979
WL - Hatzic Woodlot	81 = 1981

Slide numbers may be followed by small alphabetical letters

Patterns are used to outline the approximate area of the landslide; different patterns indicate different types of landslides.

Each landslide has a unique letter-number code.

Slide Patterns	Type of Landslide
(solid)	debris slide, flow or torrent
(striped)	slump in unconsolidated materials
(dot)	deep-seated rock landslides; type indicated on map (e.g. rockslide, rock slump)



Summary Table of Landslide Characteristics

The following table provides a summary of some of the data (about individual landslides) stored in the landslide data file.

Landslide Letter-Number Code	Type of Landslide	Slope	Characteristics of Initiation Point: Material	Location	Land Use	Vegetation Status	Entered Stream/Gully/Lake
DE-62-01	T	42	C	GH	N	+27	VS
DE-62-02	T	42	C	OS	N		VS
DE-79-03	T		A	GS	R	+03	VS
DE-81-04*	SU		A	OS	R		S
DE-81-05*	SL	35	FG	OS	N		S
DE-62-06*	SL	22	FG	OS	N	+27	S
DE-62-07*	SL	36	FG	OS	N	+27	S
DE-79-08*	SL		A	OS	R	+03	S
DE-79-8a	T		A	GC	R	+03	S
DE-81-09*	SL		A	OS	R		S
DE-68-10*	SL		A	OS	R	+11	S
DE-62-11	SL	26	M	OS	C	-25	S

Asterisk (*) indicates the landslide was observed or inspected in the field.

Figure 3: Example of part of the landslide inventory map and expanded legend

type of material, texture, surface expression (slope) and geological process. These areas are referred to as terrain polygons. Terrain polygons within the study area were identified on the 1:20 000 scale vertical air photographs, field checked in the summer of 1984, and transferred from the photographs onto a 1:20 000 scale topographic map (Fig. 4). In addition to the terrain map, a terrain data file was created to store the information for each polygon portrayed on the map and other characteristics of these areas obtained from topographic and geologic map sources (Table 2). A computer programme identified all the polygons in this file in which one or more natural landslides had taken place and transferred this information into a map data file (Fig. 2).

Landslide Rating Programme

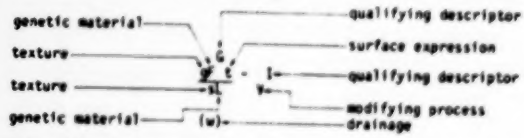
The landslide rating programme had two objectives: (1) to rate each terrain polygon as to its likelihood of clearcut landslides occurring following clearcut forest operations; and (2) to assess the likelihood of landslide debris impacting upon the stream system if a rapid mass movement should occur within a terrain polygon.

1. Clearcut Landslide Rating

A four-fold clearcut landslide rating scheme for the study area was established by: (a) analysis of the merged landslide file by various SAS procedures to identify the factors and/or site characteristics that influence natural and clearcut landslides within the study area (Fig. 2) and (b) defining a number of unique terrain classes based on these factors in a manner that each terrain polygon, based on its physical character, would be assigned to one, and only one, of these defined terrain classes. The new terrain class for each terrain polygon were subsequently stored in the map file (Fig. 2). For each terrain class a number of statistics were calculated, including: (a) the number of landslides by type (natural, clearcut, road); (b) the total area in a natural state (as of 1962) and clearcut state (as of 1981); (c) length of road; and (d) landslide frequency rates for the different landslide types on an area or length of road basis.

Explanation of Letter Notation

A combination of letters is used to designate each map unit. The relative position of letters within the symbol indicates the characteristic that they represent.



This unit is a terrace of glaciofluvial gravels that overlie lacustrine sands; the whole unit is characterized by inactive gullying and is well-drained.

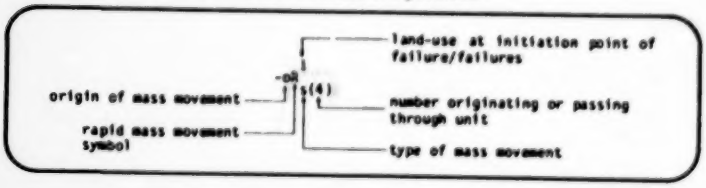
Explanatory Notes

1. Units consisting of two or more types of terrain are designated by two or more groups of letters separated by slashes and/or dots (see Composite Units below).

2. Materials underlying the surface unit are shown by a symbol that is written beneath the surface unit symbol and separated from it by a horizontal line.

3. In order to provide further details about the rapid mass movements in the study area, additional letters and numbers have been used in conjunction with the rapid mass movement process symbol (-R) (see box 9).

Rapid Mass Movement Process Symbols



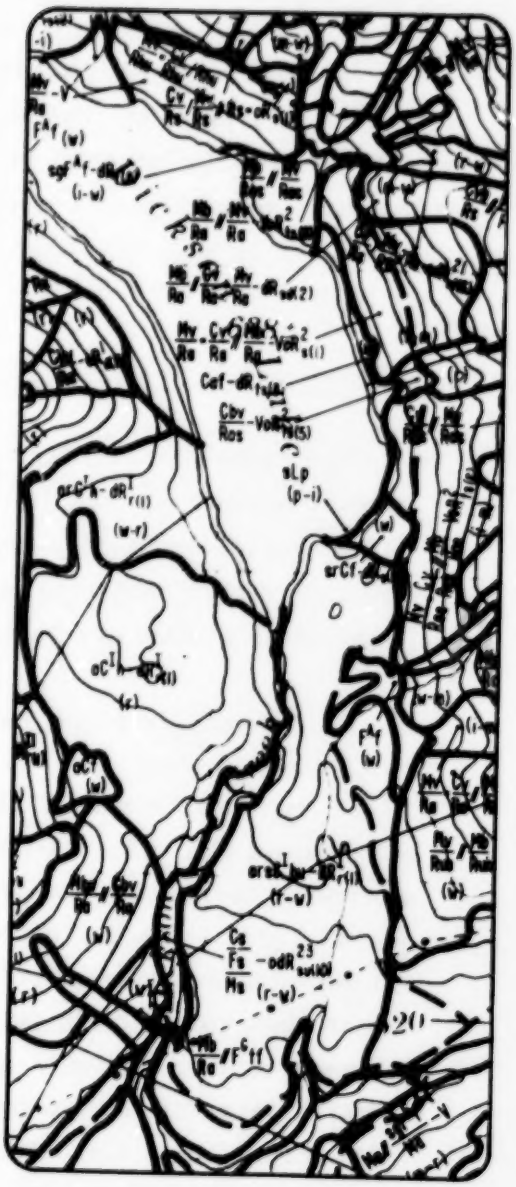


Figure 4: Example of part of the terrain (surficial geology) map and expanded legend

Table 2: Summary of terrain attributes (surficial geology) stored in terrain data file for polygons on the terrain map

Summary Table of Terrain Attributes Stored in Terrain Data File For Polygons on the Terrain Map [1]

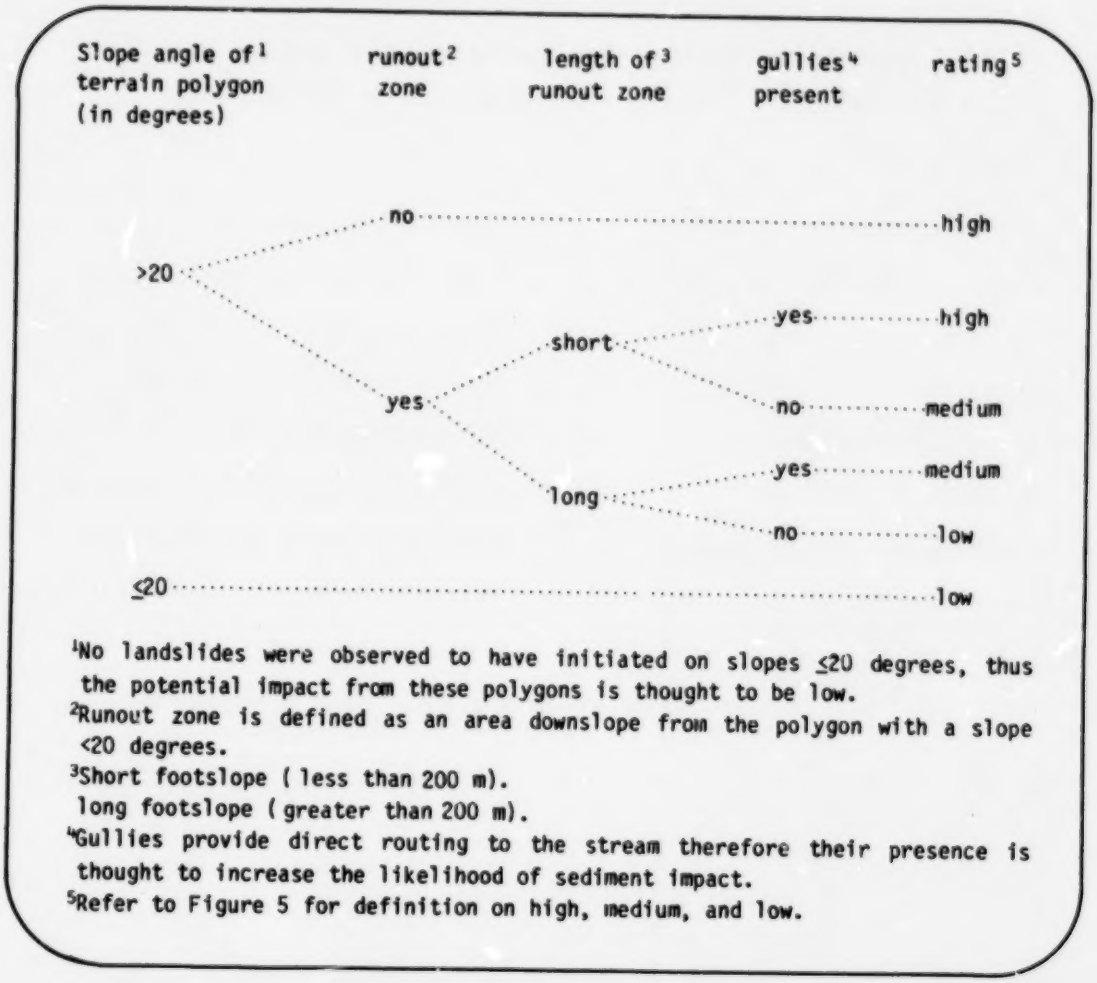
polygon identification number	aspect (range, average)
texture of surficial material(s)	slope (maximum, minimum)
drainage	slope (average)
permeability	bedrock type(s) (underlying)
surface form (configuration)	bedrock outcrops - type
thickness of materials	underlying unconsolidated materials
modifying geologic processes	texture of underlying materials
number and type of landslides (from landslide file)	length of road (km)

[1] Data sources include air photographs, field observations, topographic maps, and other related geologic maps.

Table 3: Four-level clearcut landslide rating classification (after Sondheim and Rollerson, 1985)

Clearcut Landslide Rating on the rating map	Landslide Frequency (landslides/hectare)
1	0.00 to $\leq$0.01
2	>0.01 to $\leq$0.05
3	>0.05 to <0.10
4	$\geq$ 0.10

Table 4: Qualitative rating system assessing the likelihood of a landslide impacting upon the stream system



[1]No landslides were observed to have initiated on slopes ≤20 degrees, thus the potential impact from these polygons is thought to be low.
[2]Runout zone is defined as an area downslope from the polygon with a slope <20 degrees.
[3]Short footslope (less than 200 m).
long footslope (greater than 200 m).
[4]Gullies provide direct routing to the stream therefore their presence is thought to increase the likelihood of sediment impact.
[5]Refer to Figure 5 for definition on high, medium, and low.

The clearcut landslide frequency rate for each terrain class was then assigned a clearcut landslide rating based upon an arbitrarily defined four-fold classification (Table 3). Each terrain polygon (previously assigned to a terrain class) was then assigned a clearcut landslide rating from 1 to 4. This data was transferred into the map data file.

Explanation of Map Notation

Natural mass movement rating (see A)

Clearcut landslide rating (see B)

Potential Introduced landslide debris rating (see C)

Example: • 3+:H-L

This symbol indicates that (1) natural landslides have occurred within this polygon (• symbol); (2) there is a moderate likelihood that rapid mass movements and/or slumps will occur following clearcut operations (3 + symbol); and, (3) if a landslide should occur, there is a high likelihood that the landslide debris will impact upon the stream system and possibly, be deposited into a lake (H-L symbol).

A NATURAL MASS MOVEMENT RATING

Symbol	Description
•	Indicates that at least one or more shallow rapid mass movements and/or slumps in unconsolidated material in a natural setting has initiated within the polygon.

B CLEARCUT LANDSLIDE RATING

Symbol	Description
4	Terrain polygons that have a high likelihood of clearcut rapid mass movements occurring following clearcut operations (≥0.100 failures per hectare).
3	Terrain polygons that have a moderate likelihood of clearcut rapid mass movements occurring following clearcut operations (≥0.05 to <0.100 failures per hectare).
2	Terrain polygons that have a low likelihood of clearcut rapid mass movements occurring following clearcut operations (≥0.010 to <0.05 failures per hectare).
1	Terrain polygons that have a very low likelihood of clearcut rapid mass movement occurring following clearcut operations (<0.0100 failures per hectare).
+	Terrain polygons that have a moderate likelihood of clearcut slumps occurring following forestry operations (≥0.05 to <0.10 failure per hectare).

C POTENTIAL INTRODUCED LANDSLIDE DEBRIS RATING

Potential introduced landslide debris is a qualitative rating of the likelihood of clearcut landslide debris entering the stream system if a landslide should occur within a terrain polygon. The stream system includes stream order one and two channels, and gullies.

H	There is a high likelihood of landslide debris impacting upon the stream system, if a clearcut landslide (i.e. rapid mass movement, slump) should occur in these terrain polygons. (Most of the clearcut rapid mass movements and slumps occurring in these areas are expected to impact upon the stream system).
M	There is a moderate likelihood of landslide debris impacting upon the stream system, if a clearcut landslide (i.e. rapid mass movement, slump) should occur in these terrain polygons. (Some of the clearcut rapid mass movements and slumps in unconsolidated materials occurring in these areas are expected to impact upon the stream system).
L	There is a low likelihood of landslide debris impacting upon the steam system, if a clearcut landslide (i.e. rapid mass movement, slump) should occur in these terrain polygons. (Few of the clearcut rapid mass movements and slumps occurring in these areas are expected to impact upon the stream.)
-L	This symbol is used to modify the potential introduced landslide debris rating and indicates that landslide derived debris may be deposited into a lake.

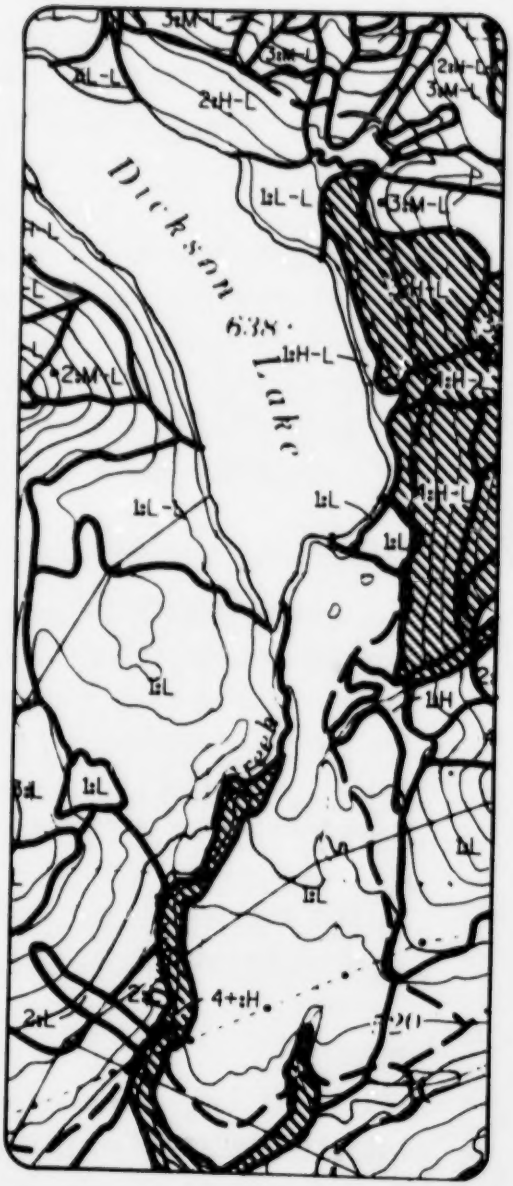


Figure 5: Example of part of the clearcut landslide and introduced landslide debris rating map and expanded legend

2. Potential Introduced Landslide Debris Rating

An introduced landslide debris rating system, based on a proposal by Church (1983), was created to assess each terrain polygon in terms of its likelihood of landslide debris impacting upon the stream system if a landslide should occur within the polygon. Factors used in this scheme include: (1) slope angle of the polygon; (2) presence or absence of a runout zone below the polygon; (3) length of runout zone; and (4) presence of gullies providing direct access to the stream channel (Table 4). Data from the landslide programme was also used in the assessment because it provided a historical record of past landslide events and the distance material travelled downslope from their initiation sites. Each polygon was assessed by these factors and placed into one of three classes (Table 4 and Fig. 5). This information was also entered into the map data file.

Clearcut Landslide and Introduced Landslide Debris Rating Map

Information in the map data file was converted by a computer programme into map notation (Fig. 5) and mechanically plotted onto a mylar base. Data stored in this file for each terrain polygon and transferred to the base included: (1) presence of natural landslides; (2) clearcut landslide rating; and (3) potential introduced landslide debris rating. The mylar base was subsequently overlaid onto a 1:20 000 topographic map of the study area and photographically reproduced (Fig. 5). A complete copy of the map is located in the map pocket and further copies are available from Maps B.C., 553 Superior Street, Victoria, B.C. V8T 1X5.

RESULTS

Landslide Programme

A total of 595 rapid mass movements were identified and mapped within the study area. They originate in the natural environment, clearcut blocks, and road beds. The number of clearcut and natural landslides are approximately equal (43% and 41%, repectively), which is similiar to the percent of the study area unmodified and modified by man (55% and 45%, respectively). The landslides occur in three topographic locations: (1) gully side and headwalls; (2) hillslopes not dissected by gullies (referred to here as open hillslopes); and (3) escarpments in unconsolidated sediments.

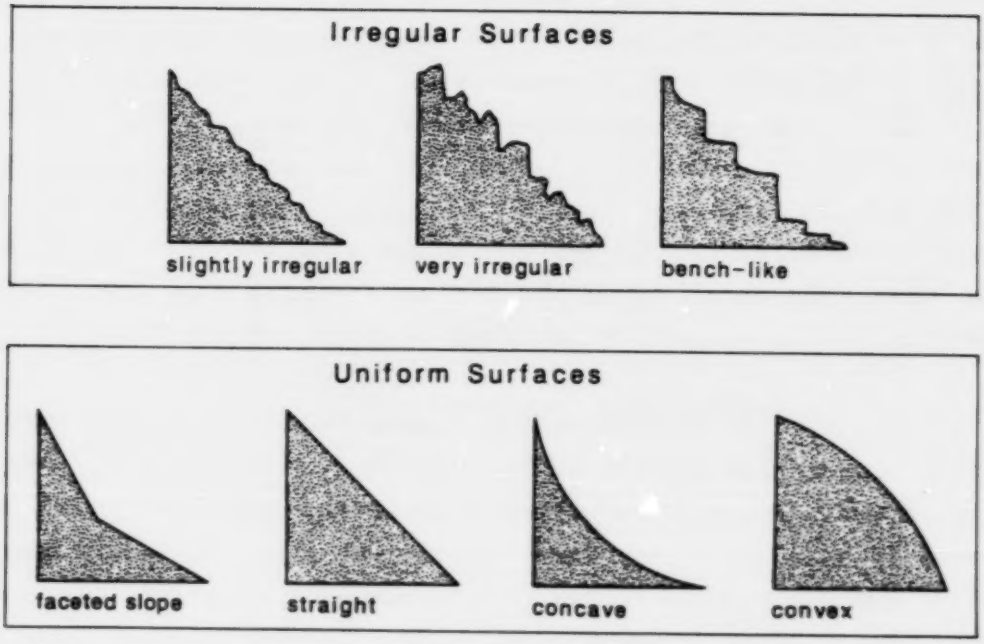


Figure 6: Examples of uniform and irregular slope configurations

Landslides are more common in terrain dissected by gullies and escarpments than on open hillslopes. For example, 15% of the terrain in the study area is undergoing gully erosion; however, 44% of all the rapid mass movements originated in gullies. Escarpments account for 3% of the area, yet 8% of the landslides originate in escarpments. In contrast to this, 72% the study area is made up of open hillslopes, but only 48% of the landslides occur on these slopes.

The rapid mass movements occur most frequently in two types of surficial materials. These are colluvium that is rapidly drained (42%) and till which is moderately to rapidly drained (36%). Landslides in road bed materials and in fluvial and glaciofluvial sediments that are rapidly to moderately drained account for the remainder (16% and 6%, respectively). The rapid mass movements are shallow failures commonly originating in local depressions on the slope. Headwall scarps range from 0.5 to 3.0 m in height and are an average of 1.1 m high. Failures in thin mantles of colluvium and till typically occur on the underlying unweathered bedrock surface or along the

weathering front in the bedrock, whereas, in thicker till deposits, failures typically originate at the contact of the unweathered and weathered till, and occasionally on basal organic accumulations in the unweathered till (see Howes, 1981). No statistical preference was observed for landslides originating in colluvium derived from the two dominate bedrock types, granitic and meta-volcanic rocks. The surface configuration of slopes adjacent to the headwall scars are predominately uniform (88%), although, at a few sites, the local topography had an irregular form (12%) (Fig. 6 illustrates examples of uniform and irregular slope configurations).

Various landslide frequencies (on an area basis) for several surficial materials were plotted against different slope classes (Fig. 7). This was done to identify if certain material and landslide types (particularly those generated in open hillslopes) have "important" slope angles in terms of landslide frequencies, that in turn, would be useful in defining the terrain classes. Conservative interpretation of this and other data suggests that (a) 26° and 33° may be important slope breaks for open hillslope till landslides because few of these landslides occur on slopes <26°, there is a large increase in open hillslope till failure frequency at the 33-35.9° slope interval followed by a slight rise in frequency at the next higher interval (Fig. 7b), and the mean slope angle of natural and clearcut till landslides generated on open slopes is 33° and 32.1°, respectively; (b) 30° and 36° appear to be important slope breaks for open hillslopes colluvium landslides because few of these landslides occur on slopes <30°, and the mean slope angle of natural and clearcut colluvial landslides is 38.2 versus 36.5°, although, it is difficult to establish a critical slope angle when location of landslide origin (gully versus open slope) is compared (Fig. 7c); (c) 33° is probably an important slope break for open hillslope landslides made up of fluvial or glaciofluvial materials as the greatest increase between slope intervals occurs at the 33-35.9° interval (Fig. 7a) and the mean initiation slope angle of these failures is 33°; (d) terrain dissected by gullies is sensitive to landslide activity, particularly on steeper slopes (Fig. 7b and c); and, (e) clearcut landslide rates are much greater than natural rates for both till and colluvial landslides regardless of slope angle (Fig. 7b and c).

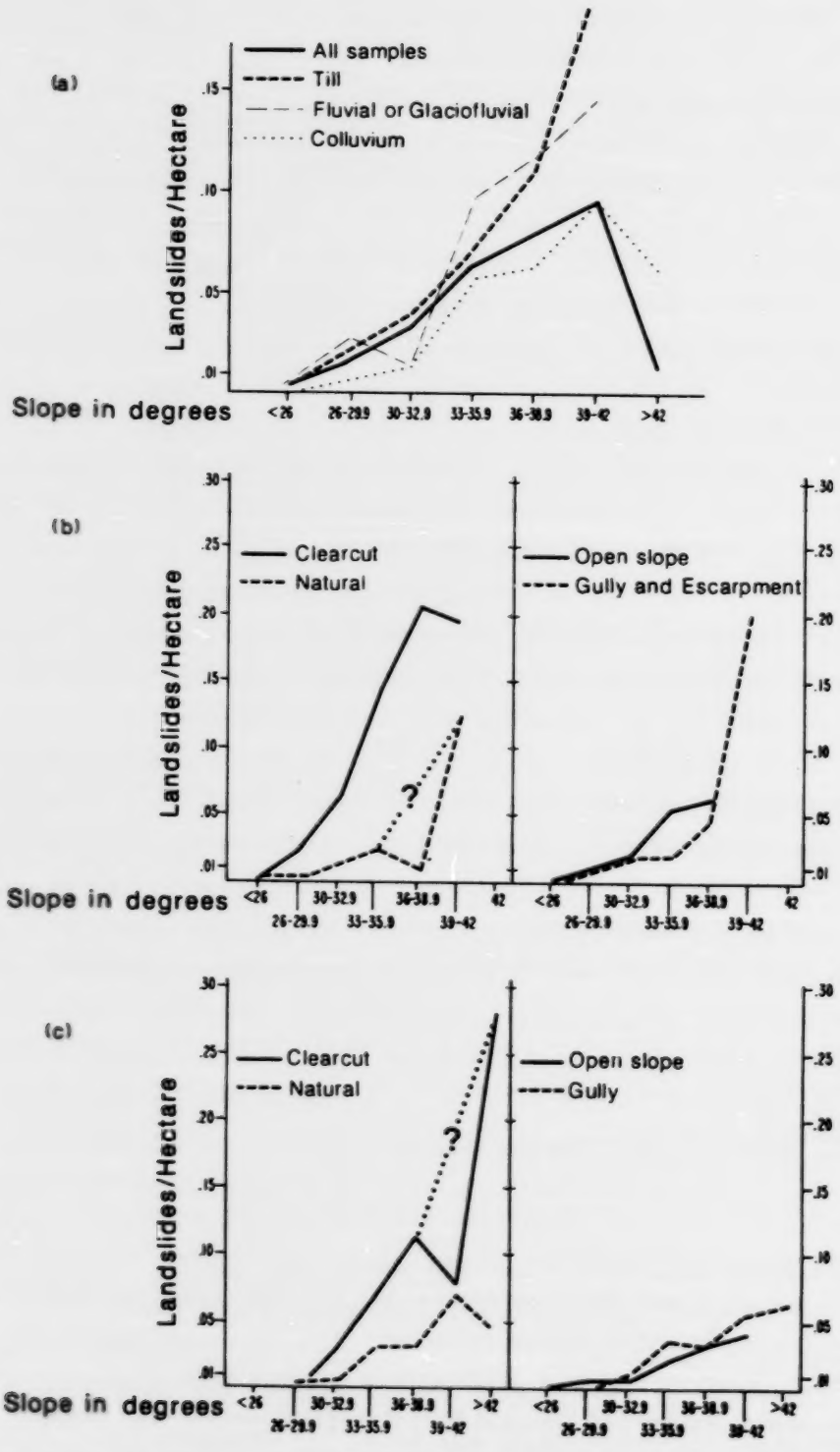


Figure 7: (a) Landslide frequencies of several surficial materials plotted against various slope classes, (b) till landslide frequencies sorted by landuse and location of the point of failure plotted against slope classes; and (c) as (b) but for landslides originating in colluvium

The observed landslide rate for natural till landslides for the slope interval 36-38.9° and clearcut colluvial landslides for the slope interval 39-42°, however, are not considered to be representative (Fig. 7b and c). Both the natural till landslide and clearcut colluvial landslide rates for these intervals are considered to be too low. The low till landslide rate is probably a consequence of the manner in which the originating material of the landslides was determined. Identification of material type on steep, forested slopes, particularly between till and colluvium, from air photographs is difficult. Thus, some of landslides may have occurred in till on these slopes, yet, were included in the colluvial count. A natural till landslide rate has been estimated for this interval (Fig. 7b). The low clearcut colluvial landslide rate for the slope interval 39-42°, like the above natural till landslide rate, is due to the few number of landslides in the class. Unlike the till landslide rate, however, it is thought to be a reflection of the small amount of recent harvesting on these steep slopes and the lack of sufficient time for the effects of clearcutting to fully impact on the landslide rate (e.g. root deterioration). An estimated rate for this interval is projected on Figure 7c.

Comparison of natural and clearcut mean slope angle for landslides originating in colluvium and till indicates that the natural slope angle is, on the average, is 0.9° to 1.7° steeper than the clearcut slope angle (see above). This and the higher clearcut landslide rates versus natural landslide rates on the different material types suggests that removal of the vegetation reduces the average slope angle for the initiation of clearcut landslides on these material types by 1 to 2°. The difference may result from a decrease in soil shear strength by root decay and/or changes in the local hydrology (see below).

Natural and clearcut landslides had a preferred north-south orientation of failure initiation point on slopes >20°. Chi-square analysis indicates that this relationship is significant at the 99% level of confidence for landslide frequency rates sorted by aspect that have been normalized by area (e.g. number landslides with a given aspect ÷ total area of the aspect). The preferred south aspect of landslide initiation points is thought to be a function of the way in which local winds move up valley in the study area,

particularly during the winter months. Many coastal storms approach the coast of British Columbia from the west or southwest and this is thought to result is a strong up-valley airflow (south to southwest) within the study area. The preferred north aspect of initiation sites is thought to be a result of different moisture conditions on these slopes versus other slopes (e.g. north slopes tend to be wetter, retain snow packs longer, and are cooler than south facing slopes within the study area).

The total volume of sediment eroded by rapid mass movements between the period of 1950 to 1981 has been estimated to be approximatley 1.1 million m^3. It was calculated in the following manner: (1) A total of 549 rapid mass movements were identified between 1950-1981; (2) The volume of material eroded by 280 of these landslides was calculated from field and/or measurements done on 1:5000 scale photography and was 560,811 m^3; (3) Assuming that the remaining 269 landslides have a similar size distribution, the volume of material eroded by these landslides was estimated to be 538,818 m^3 (560,811 ÷ 51 x 49). Thus, the total volume of material eroded by landslides between 1950-81 was 1,099,629 m^3 or about 35,471 m^3 annually. Since a total of 88% of the landslides between this period entered the stream system, about 31,225 m^3 of sediment has impacted annually upon the stream network. Similar calculations have been done on unconsolidated slumps in the study area. An estimated volume of 260,000 m^3 of material has been eroded from 42 slumps. Thirty-six percent of this volume was derived from a large, deep seated slump located in a clearcut, although, the role of forest operations on this particular mass movement is unknown. Nevertheless, the total material eroded by rapid mass movements and slumps during the period 1950-1981 has been estimated to be 1.36 million m^3 or about 43,870 m^3 annually. Contribution to the total volume eroded from different landslide types (natural, clearcut, road) over time are discussed below.

The volumes of the measured landslides have also been subdivided into four size classes, and their frequency and estimated contribution to the total volume is presented in Figure 8. This figure shows that the medium size class contributes the highest amount of material to the total volume; the large size class accounts for 3% of the total number of landslides, yet makes up 29% of the total volume, and over 80% of the landslides in each class entered the stream system. Comparison of the mean volume eroded by landslide types indicates that natural landslides ($\bar{x}$ = 2594 m^3) tend to be larger than clearcut landslides ($\bar{x}$ = 1567 m^3).

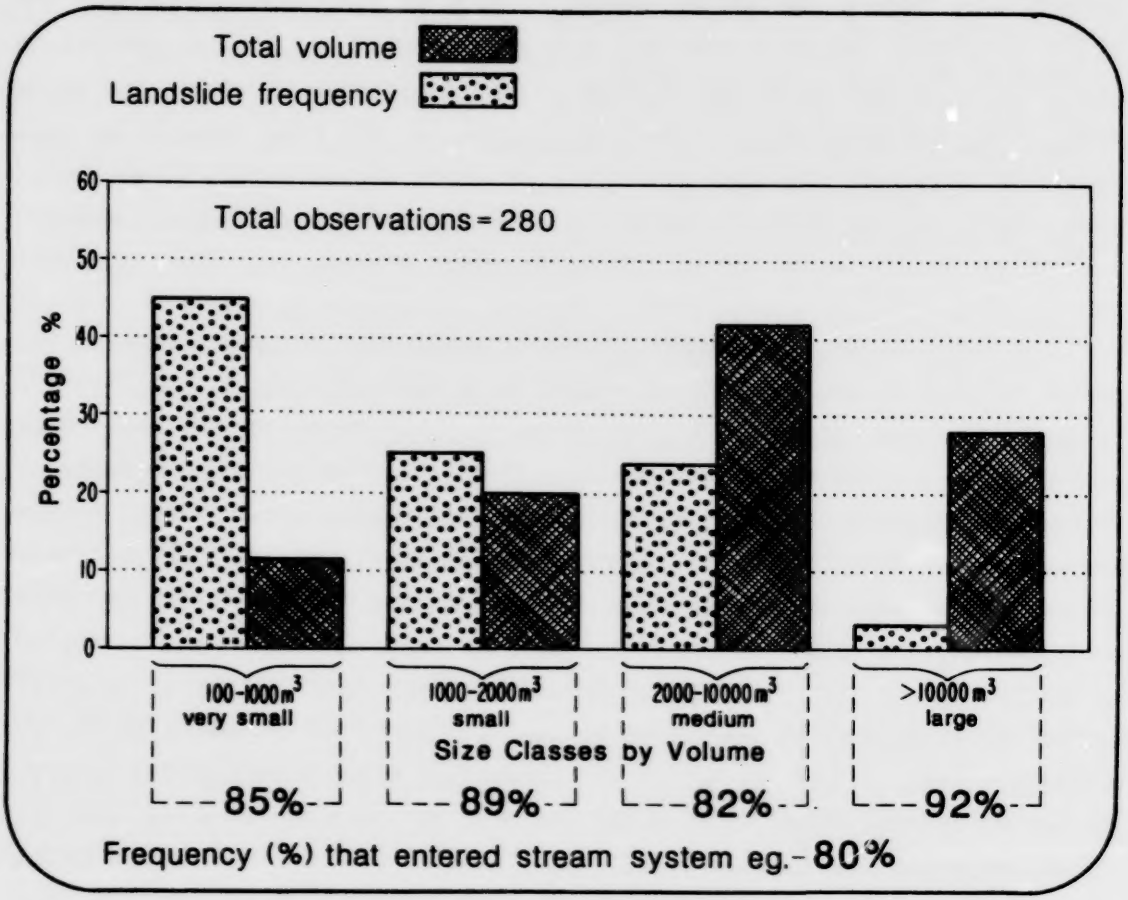


Figure 8: Landslide size classes (by volume) and comparison of the percentage frequency and estimated total volume of each size class

Subsequent revegetation of upper and middle portions of the landslide scars is slow. About 70% of all of the landslides as of 1981 were devoid of a vegetation cover. A more realistic assessment of how these landslide scars revegetate over time is reflected by the percentage of non-vegetated landslides (54% as of 1981) that were observed on the 1962 and 1968 photographs. This slow rate of revegetation is thought to be the result of post landslide surface erosion removing or buring early plant species and/or the microclimate on landslide scars inhibiting revegetation. For example, landslide scars are thought to have higher soil and surface temperatures and drier conditions than surrounding clearcut and forested terrain during the summer. No data was collected to support these conclusions; however, landslide scars, particularly those with a south aspect, observed in the

field during a warm, dry, 2-week period in the summer of 1984 were noticeably warmer and drier than the surrounding revegetated clearcuts or natural forest. Surface erosion processes are active on many of the landslide scars: 90% of the unvegetated landslide scars visited were undergoing modification by rill and/or gully erosion.

In summary, the important results of the landslide programme were:

(1) It identified several site characteristics that influence clearcut landslides that were used in the landslide rating programme (see below). Some of the more notable findings were that different material types have different 'critical' angles when various types of landslide frequencies are compared and contrasted (e.g. landslide frequencies sorted by landuse and/or location at their point of initiation); areas dissected by gullies are particularly sensitive to rapid mass movements; natural and clearcut landslides have a preferred north-south orientation at their point of failure; and the majority of landslides occur in shallow deposits of colluvium or till, typically in local depressions (seepage sites) on uniform slopes that overlie an impermeable subsurface (bedrock or unweathered till).

(2) The total volume of material eroded from the hillslope by rapid mass movements from 1950 to 1981 is estimated to be about 1.10 million m^3 (excluding slumps). Including slumps, the total is 1.36 million m^3, of which 88% impacted on the stream system. Most of this volume was generated by medium to large sized landslides although they account for a small percentage of the total number of landslides. Natural landslides, on average, tend to be larger than clearcut landslides.

(3) Revegetation of landslide scars is slow; 70% of the landslides were bare as of 1981 and 54% of the landslides that occurred on the 1962 and 1968 photographs remained devoid of vegetation by 1981. This slow rate of re-vegetation is thought to result from post-secondary surface erosion processes and/or local microclimatic conditions retarding early plant growth.

Table 5: Description of terrain classes for the study area.

TERRAIN CLASS	MATERIAL ATTRIBUTES					SLOPE ATTRIBUTES		OTHER
	Type (Landform)	Drainage	% Cover	Depth[1]	Probable Underlying Material	Angle (In Degrees)	Configuration	Gully Erosion Present[2]
1	colluvial mantles with rock outcrops	moderate to rapid	60-20	s	rock	>30	uniform	N
2	colluvial mantle	rapid	100-80	s	rock	≥36	uniform	N
3	colluvial mantle	rapid	100-80	s	rock	≥36	uniform	Y
4	constructional till landforms (rolling till plains)	moderate to rapid	100	d	unknown	<26	uniform	N
5	escarpments of fluvial, fluvioglacial, and till	rapid to moderate	100	d	till or silt	≥33	uniform	N
6	active fluvial sediments (floodplain, fan)	moderate to rapid	100	d	unknown	<20	uniform	N
	constructional fluvial deposits (fan, terrace)	rapid to moderate	100	d	unknown	<20	uniform	
	constructional colluvial deposits (fan)	rapid to moderate	100	d	unknown	<26	uniform	
7	constructional fluvial deposits (fan, terrace)	rapid to moderate	100	d	unknown	≥20-<33	uniform	N
8	till mantle	rapid to moderate	100	d-s	rock	<26	uniform	N
	mantles of till and colluvium or colluvial mantle	rapid to moderate	100	s	rock	<29	uniform	
9	colluvial mantle	rapid	100-80	s	rock	variable	irregular	N
	till mantle	rapid to moderate	100-80	s	rock	variable	irregular	
	mantles of till and colluvium	rapid to moderate	100-80	s	rock	variable	irregular	
	colluvial mantles and bedrock	rapid	60-20	s	rock	variable	irregular	
10	Marine deposits (terrace)	moderate to poor	100	d	unknown	<26	uniform	N
11	till mantle	rapid to moderate	100-80	s-d	rock	≥26-<33	uniform	N
	colluvial mantle	rapid	100-80	s	rock	>29-<36	uniform	
	mantles of till and colluvium	rapid to moderate	100-80	s	rock	≥29-<33	uniform	
12	till mantle	rapid to moderate	100-80	s-d	rock	≥26-<33	uniform	Y
	colluvial mantle	rapid	100-80	s	rock	>29-<36	uniform	
	mantles of till and colluvium	rapid to moderate	100-90	s	rock	≥29-<33	uniform	
13	fluvioglacial or colluvial sediments overlying till	rapid to moderate	100	d	till	<33	uniform	N
14	till mantle	rapid to moderate	100-80	s	rock	≥33	uniform	N
	till and colluvial mantle	rapid to moderate	100-80	s	rock	≥33	uniform	
15	till mantle	rapid to moderate	100-80	s	rock	≥33	uniform	Y
	till and colluvial mantles	rapid to moderate	100-80	s	rock	≥33	uniform	

1. d = >1.5 m, s = <1.5 m
2. Y = gully erosion present, N = no gully erosion

Rating Programme

Site factors that influence the initiation of clearcut landslides determined from the landslide programme and used in the initial definition of the terrain classes were: (1) type of material and drainage; (2) depth and percent cover of surficial material; (3) slope angle, which varies for different material types; (4) slope configuration; (5) presence of gully erosion; and (6) aspect. Aspect, however, was not included as a definitive factor in the final definition of the terrain classes because the inclusion of this factor during preliminary analysis resulted in too small sample sizes for some of the terrain classes. It was noted on the users map, however, that aspect should be considered in any on-site investigation. A total of 15 terrain classes were defined by unique combinations of the remaining factors (Table 5).

Various statistics for each terrain class, such as landslide frequencies, were calculated and are presented in Table 6. Terrain with the highest number of clearcut landslides per hectare includes: (a) till, or till and colluvial mantles with uniform slopes $\geq$ 33° dissected by gullies; (b) colluvial mantles on uniform slopes $\geq$ 36° that are dissected by gullies; and (c) escarpments of unconsolidated sediments with slopes $\geq$ 33°. These and other statistics also illustrate the following:

1. There is a close agreement between the natural, clearcut, and road landslide frequencies for each terrain class. For example, terrain classes that have a high or moderately high natural landslide rate ($\geq$ 0.03 slides/hectare) have corresponding high or moderately high clearcut and road landslide rates (clearcut rating of 4 or 3, or $\geq$ 0.8 road failures/km) (see terrain classes 3, 5, 12, 14, and 15). The clearcut landslide rates for terrain classes 1 and 2 (see Table 5 for their description) are an exception to this pattern. No clearcut landslides have occurred in terrain class 1 and the clearcut rate for class 2 is slightly lower than the natural rate (although the road landslide rate is high). This difference between natural and clearcut rates may be explained, in part, by the amount and age of the clearcuts on steep colluvial terrain. It is thought that an insufficient amount of time has passed for the complete effects of harvesting to affect the clearcut rate of these terrain

Table 6: Landslide frequencies and clearcut rating for the terrain classes of the study area

TERRAIN CLASS	NUMBER OF RAPID MASS MOVEMENTS			AREA (hectares)/LENGTH (km)			LANDSLIDE FREQUENCY RATES			CLEARCUT [6] RATING
	Natural	Clearcut	Road	Total [1] Natural Area	Total [2] Clearcut Area	Total [2] Road Length	Natural [3] (per hectare)	Clearcut [4] (per hectare)	Road [5] (per km)	
1	20	0	2	427	82	2.27	0.0469	0.0000	0.8810	2**
2	51	17	5	745	299	4.20	0.0684	0.0569	1.1904	3
3	34	20	5	546	177	2.88	0.0622	0.1130	1.7361	4
4	0	5	6	522	630	19.08	0.0000	0.0080	0.3145	1
5	14	41	13	284	352	8.84	0.0493	0.1165	1.4705	4
6	0	1	2	804	893	24.64	0.0000	0.0011	0.0812	1
7	0	5	3	133	101	5.76	0.0000	0.0495	0.5208	2
8	8	13	9	1178	903	30.17	0.0067	0.0111	0.2983	2
9	3	5	6	3083	1256	41.39	0.0013	0.0043	0.1450	1
10	0	0	0	69	0	.14	0.0000	0.0000	0.0000	1
11	22	34	17	1971	870	31.98	0.0112	0.0391	0.5316	2
12	30	50	17	808	674	19.07	0.0371	0.0890	0.8915	3
13	0	0	2	205	338	13.69	0.0000	0.0000	0.1461	1
14	30	26	8	605	275	8.16	0.0496	0.0945	0.9804	3
15	13	39	4	412	187	2.86	0.0316	0.2086	1.3986	4
Total	225	263	99	11792	7036	215.13	0.0191	0.0374	0.4601	—

1. As of 1962
2. As of 1981
3. = natural landslides/total natural area
4. = clearcut landslides/total clearcut area
5. = road failures/total road length
6. Based on the following clearcut landslide rating:
   1 = 0.0 to ≤0.01 failures/hectare
   2 = >0.01 to ≤0.05 failures/hectare
   3 = >0.05 to <0.10 failures/hectare
   4 = ≥0.10 failures/hectare

**This terrain class has a clearcut landslide rating of 2 due to its natural rate and lack of clearcut landslides.

Table 7: Comparison of landslide rates of terrain classes illustrating the effect of slope on landslide rate

Till mantles on uniform slopes

Terrain Class	Slope Angle (in degrees)	Landslide Frequency[1] Natural	Clearcut	Road
8	<26	.0067	.0111	.2983
11	≥26-<33	.0112	.0391	.5316
14	≥33	.0496	.0945	.9804
14÷8		7.4	8.5	3.2

Colluvial mantles on uniform slopes

Terrain Class	Slope Angle (in degrees)	Landslide Frequency Natural	Clearcut	Road
8	<29	.0067	.0111	.2983
11	≥29-<36	.0112	.0391	.5316
2	≥36	.0684	.0569	1.1904
2÷8		10.2	5.2	3.9

[1]From Table 6.

classes (see discussion above). Nevertheless, the close agreement between natural and clearcut landslide frequencies suggests that the presence of natural failures is a valid indicator of terrain susceptible to potential clearcut failures.

2. Natural, clearcut, and road landslide frequencies increase as slope angle increases on uniform open slopes made up of till or colluvium. On slopes overlain by a till mantles, the natural, clearcut, and road landslides are 7.4, 8.5, and 3.2 times greater, respectively, on steeper slopes versus gentler slopes (Table 7). Similar increases occur in these landslide rates on steep versus gentle slopes made up of colluvial mantles (Table 7).

3. The role of terrain dissected by gullies on clearcut rapid mass movements is demonstrated by the increase in clearcut landslide frequencies of terrain classes that only differ by the presence of gully erosion. For example, steep slopes overlain by till or colluvium that are undergoing gully erosion have higher clearcut landslide frequencies than similar terrain without gullies (see terrain classes 14 and 15, or 2 and 3).

4. Most of the terrain classes that have high clearcut landslide rates are characterized by shallow materials, usually < 1.5 metres thick, and uniform slopes (see terrain class 2, 3, 12, 14, and 15). Escarpments of unconsolidated materials (terrain class 5) is an exception. These materials are thick; however, the presence of beds of impermeable till or silt (within the gravel) impedes downward drainage which favours landslide activity at these sites. Terrain dominated by irregular surfaces (terrain class 9) have low natural and clearcut landslide rates, although slopes locally in this type of terrain may range up to 40°.

5. The clearcut rate varies from 0.83 to 6.6 times the natural rate for individual terrain classes (Fig. 9). The greatest increases occurred on moderate to steep slopes overlain by till mantles dissected by gullies (terrain class 12 and 15), mantles of till and/or colluvial materials on irregular slopes (terrain class 9), till mantles or fluvial deposits with moderate slopes (terrain class 11 and 7), and escarpments (terrain class 5). The increase of the clearcut landslide rate in the latter types of terrain (class 5, 7 and 11) is tentatively thought to result from more pronounced changes in the local hydrological (drainage) conditions on these sites than on other types of terrain. This is, in part, supported by data obtained during the landslide survey that indicates a 48% increase in the number of clearcut versus natural landslides on moderately drained sites of these material types. Also, most of these terrain classes are situated on middle to lower moisture receiving slopes; thus there may be a greater potential for changes at these sites in the surface and subsurface drainage conditions following clearcut logging. The high increase of clearcut landslides on terrain dissected by gullies reinforces other observations (see above) that this type of terrain is sensitive, with respect to clearcut landslide activity whereas the cause of the increase in class 9 is not known. This data, however, indicates that the difference between natural and clearcut rates between terrain classes can not be used for the basis of a stability rating

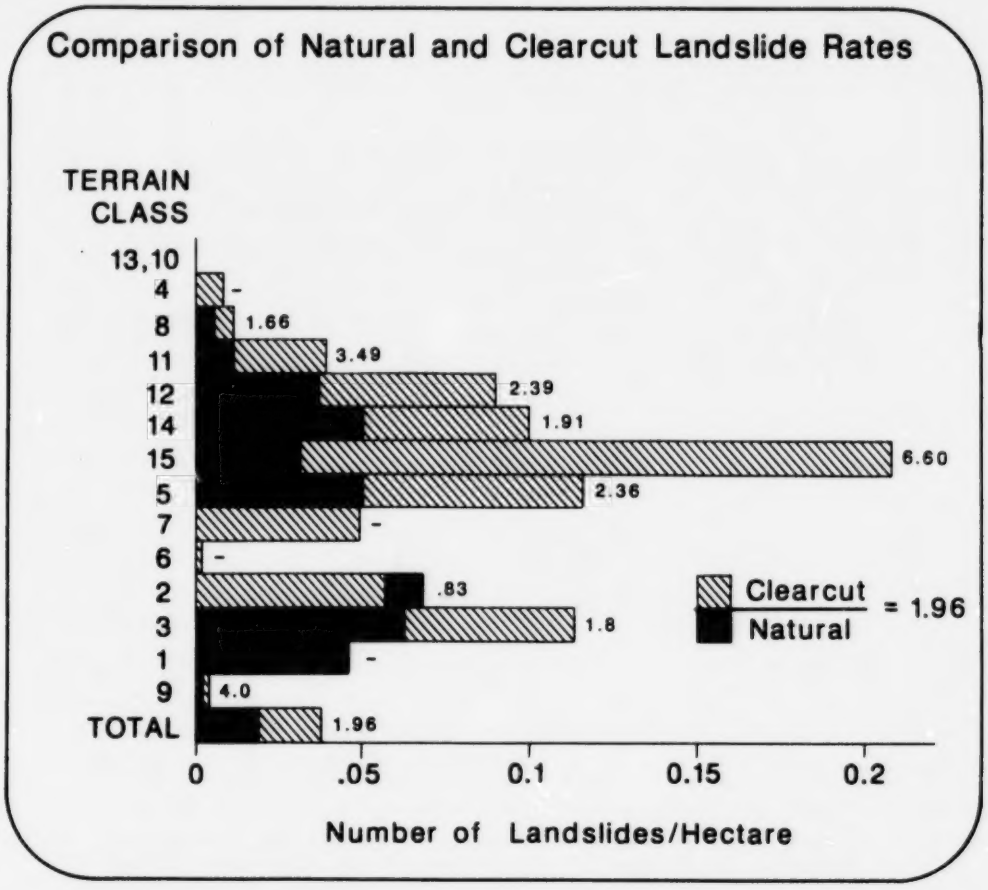


Figure 9: Comparison of natural and clearcut landslide rates by terrain class

and the relative increase in clearcut rates can not be judged from the natural rate.

6. Another statistic calculated for each terrain class was the number of terrain polygons that had one or more clearcut landslides occur within their boundaries ÷ the total number of polygons for the class. These probability statistics were plotted against the various clearcut landslide rates for each class (Fig. 10). A strong, positive, somewhat non-linear relationship exists between these statistics and suggests that the probability statistic may be used to define stability ratings for studies lacking area data (see also Rollerson et. al., 1986 and Howes and Sondheim, 1987).

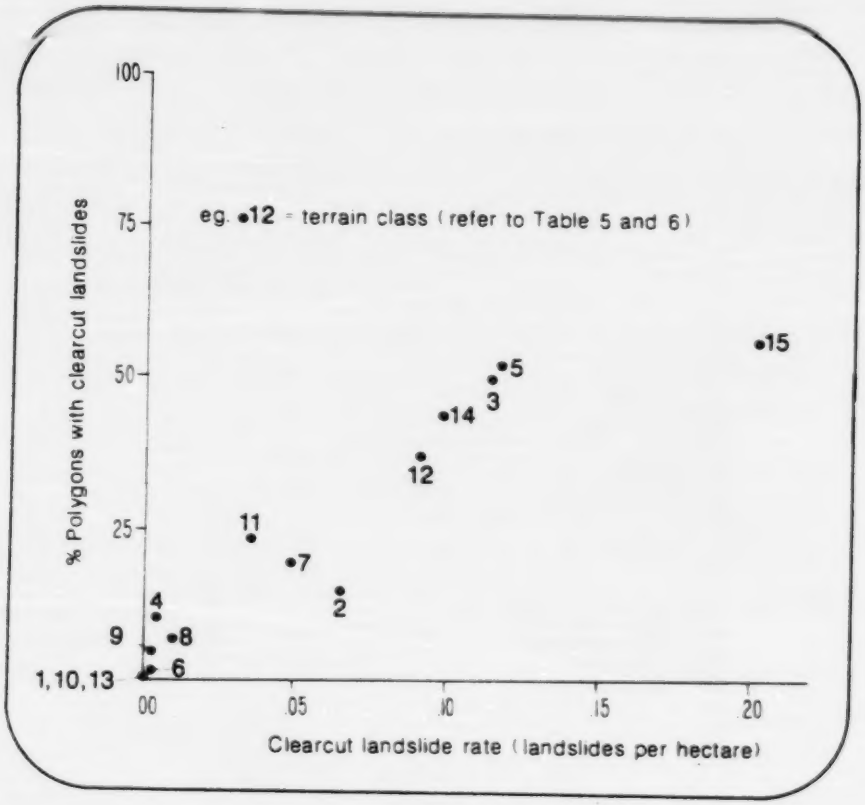


Figure 10: Comparison of clearcut landslide rates to percentage of terrain polygons that have clearcut landslides for each class.

CHANGES IN LANDSLIDE RATES AND VOLUMES OVER TIME

Natural and clearcut landslide rates were plotted over time in order that they could be compared to documented changes in the precipitation record since 1940 for the nearby town of Agassiz (Fig. 1 and 11). The precipitation data, presented in Figure 11a, was calculated by Miles (1985) using the "cumulative percentage departures from the mean" technique (see Buishand, 1982, for details) and shows historical variations in the annual and 24-hour precipitation record for the Agassiz station. This data indicates that, from the 1920's to the 1950's, annual and maximum 24-hour precipitation totals were, on average, less than normal, while from the 1950's to 1983 annual and maximum 24-hour precipitation were greater than the long-term average (Miles, 1985). For example, the average annual and 24-hour precipitation increased

Table 8: Natural and clearcut landlside rates over time

Natural Rates

Year	# Failures	Natural Area (Hec.) total	slopes >26°	Landslide Rate total	slopes >26°
41-62	123	15609 [1]	8821 [1]	.0079	.0139
62-81	67	11792 [2]	7426 [2]	.0057	.0090

[1] as of 1941 [2] as of 1962

Clearcut Rates

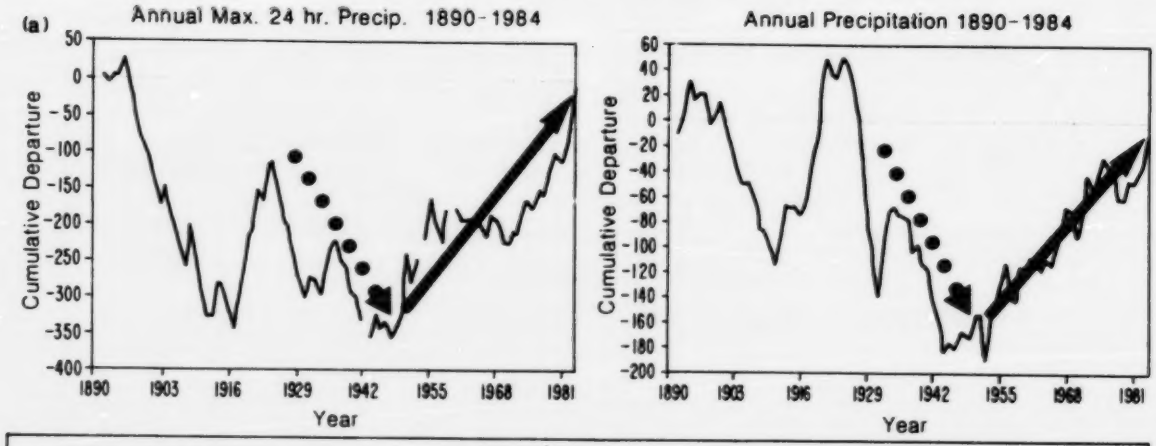
Year	# Failures	Clearcut Area (Hec.) total	slopes >20°	Landslide Rate total	slopes >20°
53-62	62	3817	2507	.0162	.0247
63-81	201	7036 [1]	4723 [1]	.0285	.0425

[1] includes area clearcut between 1953-62

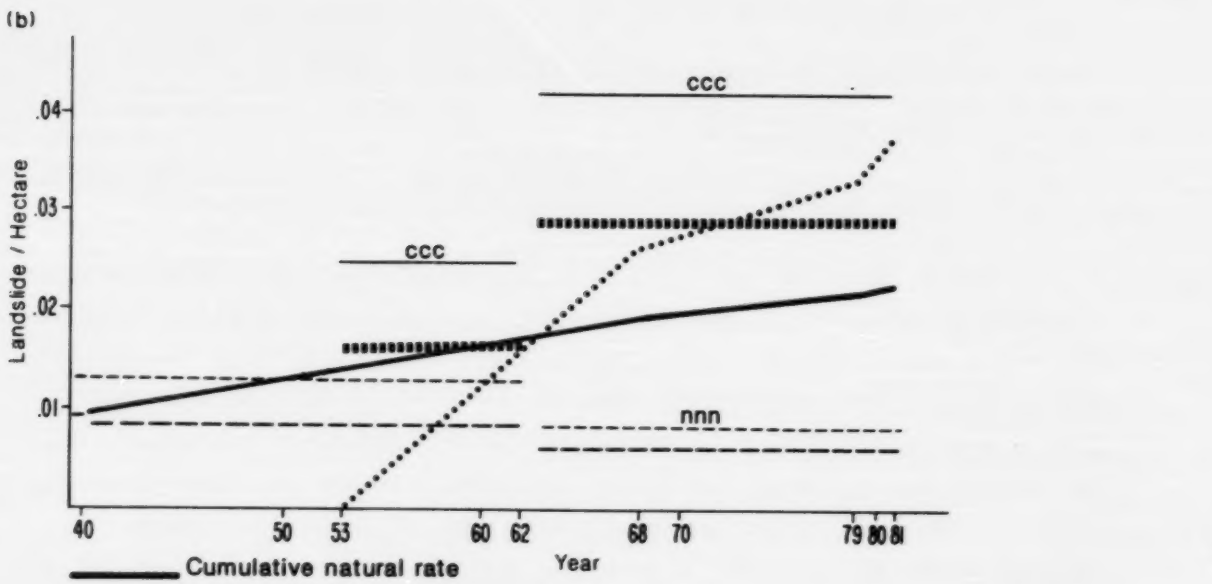
by 15% and 21%, respectively, during this latter period in contrast to the earlier period. The precipitation record during the 1953-1983 period is characterized by increasing wetter conditions through the 1960's and 1970's, with the wettest interval occurring during the early 1980's.

Clearcut landslide rates based on the total clearcut area and area of clearcuts on steep slopes for defined time periods correspond closely to the historical precipitation trends (Table 8 and Fig. 11b). For example, the clearcut landslide rate between 1963-81 (an interval of increasing 'wetter' conditions) is 1.76 times the 1953-1962 clearcut rate when the rate is based on total clearcut area, or 1.72 times the 1953-62 clearcut rate when clearcuts on steep slopes are considered. The difference in clearcut rates between these two periods is probably greater than indicated because the 1963-81 rates were calculated using all clearcut areas cut since 1953 and many of these older clearcuts stabilized ten years earlier (e.g. revegatated). In contrast to the clearcut rates, the natural landslide rates for defined time periods suggest that the natural landslide rate has essentially remained constant since 1940 for the total natural area and natural area with steep slopes (a slight decrease occurred during the 1963-1981 period). The difference between the natural and clearcut landslide

AGASSIZ[1]


(a)
Annual Max. 24 hr. Precip. 1890-1984
Cumulative Departure
Year
Annual Precipitation 1890-1984
Cumulative Departure
Year
Maximum 24 hour and annual precipitation, on average, less than normal
Maximum 24 hour and annual precipitation, on average, higher than normal

(modified from Miles, 1985)


(b)
Landslide / Hectare
ccc
ccc
nnn
Year
Cumulative natural rate
Cumulative clearcut rate
Natural rate for period indicated (#landslides during period/total natural area)
Clearcut rate for period indicated (#landslides during period/total clearcut area)
nnn Natural rate for period indicated (#landslides during period/total natural area>26°)
ccc Clearcut rate for period indicated (#landslides during period/total clearcut area>20°)

1 Refer to figure 1 for location

Figure 11: (a) Historical variations in annual and maximum 24-hour precipitation for Agassiz, British Columbia, and (b) various natural and clearcut landslide rates plotted over time

rates suggests that the removal of the forest cover has strongly influenced the clearcut landslide rate in this watershed probably by increased soil moisture conditions (due to reduced evapotranspiration rates and changes in volume and rate of snow melt) and/or the reduction of root reinforcement. The higher clearcut rate since 1962 does not appear to be a result of increased logging activity on steeper slopes. The rates have been normalized for slope and the area clearcut between 1953-62 and 1963-81 is almost equal (Table 8 - slightly more area clearcut between 1953-62). This suggests that clearcut landslide rate has been further aggravated by increasing "wetter" conditions during the past 28 years.

Volumes of material eroded by landslide types (natural, clearcut, road) between 1950-1981 also reflect the above changes in landslide rates and changes in landuse over time within the watershed (Fig. 12). For example, natural landslides were the major contributor of sediment eroded between 1950-62, whereas, between 1963-1979, clearcut landslides provided more material to the volume total than the natural landslides (Fig. 12). Although the clearcut landslide rate was slightly higher than the natural rate between 1950-1962, there were more natural than clearcut landslides. The latter observation, and the fact that natural landslides tend to be larger than clearcut landslides, accounts for the greater contribution of these landslides to the volume of eroded sediment. During the 1960's and 1970's clearcut landslides, although smaller in size, increased in terms of absolute numbers, as well as on an area basis to natural landslides, to the extent that they became the major contributor to the volume of material eroded. The high amount of material eroded from road landslides in 1980-1981 is thought to have resulted from an increase in logging activity and road construction in the late 1970's and possibly, from lack of maintenance of many roads constructed in the late 1950's, the 1960's, and early 1970's.

SUMMARY

The terrain evaluation method for landslide prediction presented is considered to more objective and quantitative than past terrain evaluations used in British Columbia. The approach uses and integrates landslide site data and areal surficial geologic data to develop natural and clearcut landslide frequency rates on a unit area basis for different types of

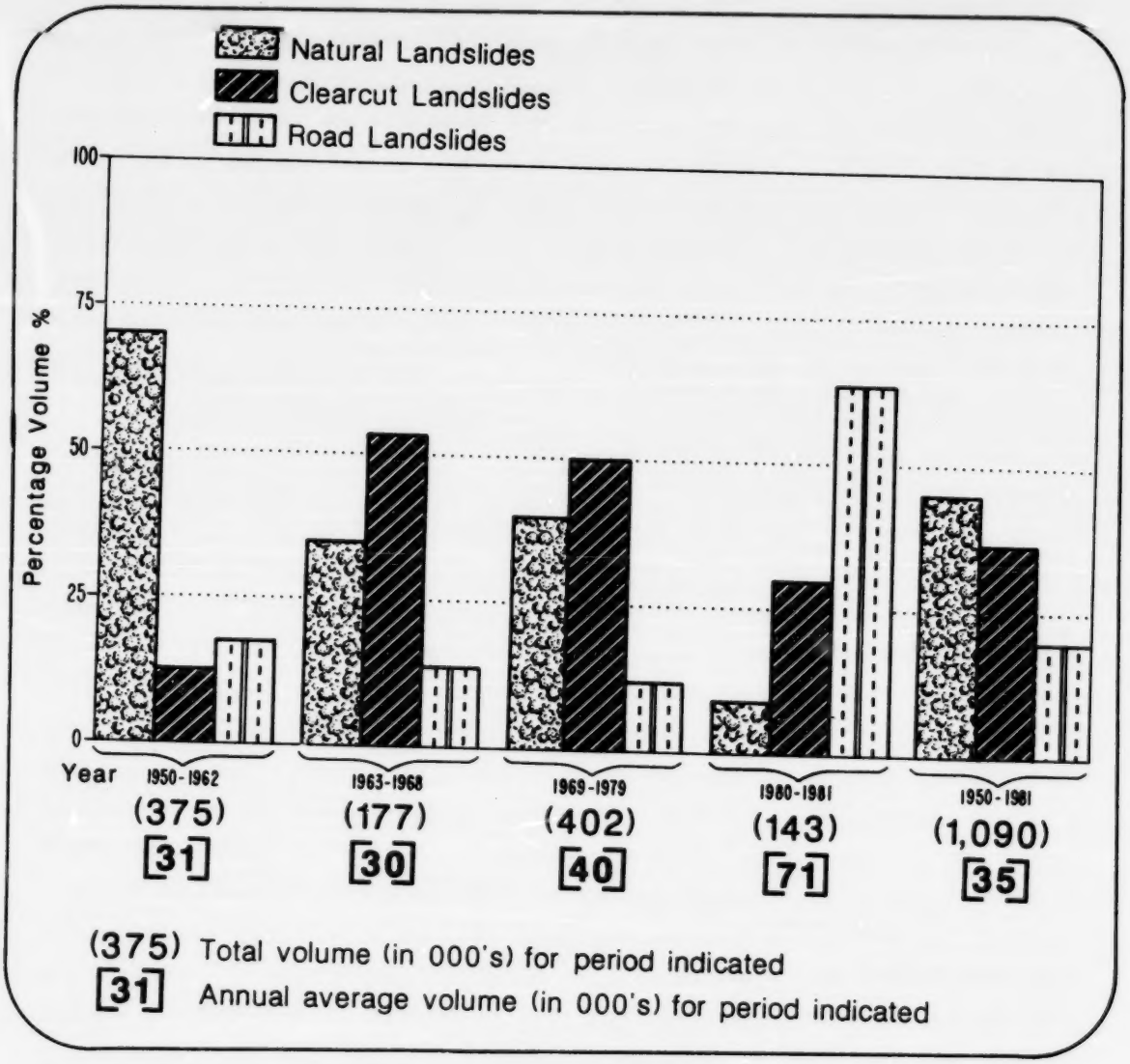


Figure 12: Estimated volumes of material eroded by landslide types between 1950-1981

terrain. This allows clearcut landslide rates for the different terrain classes to be assigned a potential clearcut landslide rating from a four-level classification. The products of this methodology include a landslide inventory map, a detailed surficial geology map, and a clearcut landslide and introduced landslide debris rating map.

Terrain with the highest clearcut landslide rates within the study area includes till or till/colluvial mantles on slopes $\geq$ 33° and colluvial mantles on slopes $\geq$36° that are dissected by gullies, and escarpments of

unconsolidated sediments with slopes $\geq$ 33°. The clearcut landslide rate varies from 0.83 to 6.6 times the natural rate on different terrain types and the 1963-81 clearcut landslide rate is 1.72 time the 1953-62 clearcut rate for clearcuts on steep slopes. In contrast, the natural landslide rate has essentially remained constant since 1940. The difference between the clearcut and natural landslide rates over this period tentatively suggests that the removal of the forest cover has strongly influenced the clearcut rate by increased water imputs and soil moisture changes and/or the reduction of root reinforcement, aggravated by increasing wetter conditions from 1953 to 1981.

An estimated volume of 1.36 million m^3 was eroded between 1950-1981 by rapid mass movements (81% of the total) and slumps (19% of the total) from the hillslopes of which about 88% entered the stream system. The contribution of natural and clearcut landslides to this total varies over time. Natural landsides were the major contributor from 1950-1962, whereas clearcut landslides became the dominant contributor during the remaining 1960's and 1970's.

During the study, several areas of potential research were identified. These include: (a) the application of the results of this study to nearby watersheds to test to what geographical extent the method may be applied; (b) exploration of the possible use of digital terrain models to improve the system for assessing the potential impact from landslides on the stream system (this would include a detailed inventory of the character of landslide runout zones); (c) further studies detailing the natural landslide rate on different terrain types during the period of precipitation change from 1940 to 1985); (d) studies related to the revegetation of landslide scars to identify the processes that inhibit or slow revegetation; and (e) the possible use of satellite imagery for long term monitoring of clearcut landslide activity.

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